

SPACE-TIME PROPERTIES OF HADRONIZATION FROM NUCLEAR DEEP
INELASTIC SCATTERING

W. K. BROOKS¹

*Physics Division, Thomas Jefferson National Accelerator Facility, Newport News,
Virginia, U.S.A.*

Received 15 October 2003; Accepted 26 April 2004
Online 22 October 2004

Hadronization, the process by which energetic quarks evolve into hadrons, has been studied phenomenologically for decades. However, little experimental insight has been gained into the space-time features of this fundamentally non-perturbative process. New experiments at Jefferson Lab, in combination with HERMES data, will provide significant new insights into the phenomena connected with hadron formation in deep inelastic scattering, such as quark energy loss in-medium, gluon emission, and color field restoration.

PACS numbers: 13.85.Hd,

UDC 539.121

Keywords: hadron formation, deep inelastic scattering, quark, gluon

1. Introduction

Hadronization has been a ubiquitous feature of high energy physics experiments for more than two decades. The subculture that has evolved around the study of this process has succeeded in characterizing the topological features of high energy jets, such as the fragmentation functions that describe the probabilities of quarks of a given flavor evolving into particular hadrons. The string picture is an example of a successful phenomenology that captures the important features over a wide range of energies. Few aspects of hadronization, however, are presently understood at the most fundamental level, since it is a non-perturbative process.

One important type of experimental data that is generally not easily accessible for hadronization is its space-time development. While some phenomenological models can be used to predict this development, the process takes place on a microscopic distance scale that is not directly observable. However, this type of information can be inferred by implanting the hadronization process into a nucleus, which acts as a spatial filter. Fully formed hadrons in the nuclear medium interact via ordinary hadronic cross sections; by contrast, propagating quarks do not

appear to interact in a way that modifies hadron yields significantly. Therefore, much can be learned from studying hadron production in deep inelastic scattering kinematics (DIS) from nuclei of varying sizes. The degree of modification of fragmentation functions, for instance, can be studied as a function of nuclear size A , energy transfer ν , hadron energy fraction $z = E_h/\nu$, and the momentum component perpendicular to \mathbf{q} , which is labelled p_T . These studies can yield important insights into the fundamental processes driving hadronization, such as gluon emission and the temporal evolution of the truncated color field following hard interactions.

Several previous measurements of semi-inclusive leptonproduction of hadrons from nuclei have been performed. The earliest generation of these were carried out with electron beams at SLAC [1] and muon beams at CERN [2] and FNAL [3]. Prominent features displayed by these efforts are an attenuation of hadrons which increases with A and vanishes with increasing ν . Following these early efforts, recent data [4,5] from the HERMES experiment at DESY [6] have inspired a new wave of theoretical interest. Unlike the historical efforts, these new data offer excellent hadron identification and high precision, allowing the flavor dependence of hadron formation to be studied.

Finally, existing and future measurements at Thomas Jefferson National Accelerator Facility (Jefferson Lab) will offer unique capabilities to study hadron production in DIS. Measurements at the CEBAF Large Acceptance Spectrometer (CLAS) at Jefferson Lab [7] will provide data on the widest possible range of nuclear target masses at high luminosity. The first data at 5 GeV were taken in 2003 with sustained luminosities approaching $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, while 11 GeV data are planned for the future, accompanied by an order-of-magnitude luminosity increase and improved particle identification using the upgraded CLAS (“CLAS⁺⁺”).

The scientific topics connected with these studies are also important themes in other physics communities. Quark propagation through strongly interacting media is a foundational element in predicting signatures of the quark gluon plasma at RHIC through the phenomenon of jet quenching [8]; in this connection, it has been explored in ultrarelativistic d-A collisions [9]. It has also been investigated in the Drell-Yan process at FNAL in studies of quark energy loss in the nuclear medium [18].

2. Experimental tools

A primary experimental tool for nuclear hadron formation is the *hadronic multiplicity ratio*:

$$R_M^h(z, \nu, p_T^2, Q^2, \phi) = \left\{ \frac{N_h^{\text{DIS}}(z, \nu, p_T^2, Q^2, \phi)}{N_e^{\text{DIS}}(\nu, Q^2)} \right\}_A \bigg/ \left\{ \frac{N_h^{\text{DIS}}(z, \nu, p_T^2, Q^2, \phi)}{N_e^{\text{DIS}}(\nu, Q^2)} \right\}_D \quad (1)$$

where N_h^{DIS} and N_e^{DIS} denote the number of hadrons and electrons measured in DIS kinematics, Q^2 is the four-momentum transfer, and ϕ is the angle between the lepton scattering plane and the photon-hadron plane. The primary connection to

theory has traditionally been through R_M^h interpreted in a partonic framework, for particular flavor combinations. Additional tools include *energy and angular correlations* between outgoing hadrons involved in the reaction. There are at least two classes that may be of interest: correlations between two energetic hadrons formed directly from the hadronization of the struck quark, and correlations between the energetic hadrons and very low energy protons. The p_T distribution is expected to become broader for larger nuclei; this *transverse momentum broadening* is expected to be large enough to be directly measurable [10]. In addition to these quantities, *polarization observables* such as single spin asymmetries may also play a role.

A variety of physical properties can be derived from the above observables. Hadron *formation lengths*, the characteristic distances over which hadrons form, can be extracted from R_M^h . *Quark energy loss* in passing through the nuclear medium may also be accessible, particularly via transverse momentum broadening, which is also closely connected with a *quark-gluon correlation function*. Correlations between final-state particles are expected to shed light on the reaction mechanisms, and the nature of the interaction with the nuclear medium, whether partonic or hadronic.

A variety of experimental capabilities are required in order to fully exploit the observables discussed above. Access to the detailed multivariate dependences of R_M^h requires a large statistical sample; this can be most economically accessed at high luminosity. Isolating the energy and angular correlations requires large acceptance, since the kinematic variables of the particles of interest are not strongly correlated. Good particle identification for several hadron species is required to analyze the flavor dependence of observables. A large energy range is needed to understand the ν dependence as well as test the validity of parton model assumptions. Polarization is needed to study such quantities as single spin asymmetries. Accessing all of these experimental ingredients will require combining information from several different facilities.

3. Model descriptions and contact with observables

Lattice computations can address nonperturbative processes in QCD. However, there are several difficulties in applying this technique to hadronization. A natural choice to describe the time development of the process is Minkowski space, however, this introduces some significant technical obstacles. In addition, the relevant space-time volume needed requires a very large lattice compared to calculating static properties of hadrons. These calculations may become feasible in the 5–10 year time frame.

Therefore, to make progress on this topic, modeling is needed. Most relevant are models possessing close contact to QCD, and which can predict a wide variety of observables. A synopsis of model approaches is given in the following section.

3.1. Models

Historically, a number of models have been developed to describe hadron production in nuclear DIS. While it is not practical to review the older models here,

a representative approach by Bialas and Chmaj [11] is instructive. In this model, the struck quark evolves into a hadron with a characteristic time τ . The probability that the propagating object is a quark at a given time t after it is struck is $P_q = e^{-t/\tau}$ and the corresponding probability that it has become a hadron is simply $P_h = 1 - P_q$. Phenomenological cross sections for the quark and hadron interacting with the nuclear medium are postulated: σ_q and σ_h . The probability of the quark or hadron interacting with the nuclear medium is taken as proportional to the density of the medium for a spherical nucleus, using a standard density parameterization. R_M^h can then be calculated by numerical integration. This model approach was qualitatively successful in describing the ν dependence of R_M^h for the HERMES nitrogen data [4], but failed to describe the z dependence even qualitatively.

In a more sophisticated approach, the gluon bremsstrahlung model [12] divides the hadronization process into several stages. As the struck quark propagates, an initial stage of uninhibited gluon emission occurs, followed by a second stage of reduced gluon emission. The suppression of gluon emission in the second stage is imposed to conserve energy, since the propagating quark begins with only a finite amount of energy, ν . At some point in the second stage, a color dipole is formed from the struck quark and the last emitted gluon. The color dipole subsequently evolves into a hadron. The role of the nuclear medium is to modulate the rate at which the color dipole turns into a hadron, including the effect of color transparency; in later versions of the model, medium-stimulated gluon emission is included, which has a small effect on the prediction for R_M^h . The assumptions of the model are valid for pions with $z > 0.5$. Its predictions agree well with the HERMES nitrogen data in both the z dependence and the ν dependence.

A more recent model approach to describing hadron production in nuclear DIS is based on a continuous series of developments since the late 1980's addressing jet quenching in relativistic heavy ion reactions [8]. In this approach, the prediction for the behavior of R_M^h is based solely on medium-stimulated gluon emission; hadronization is assumed to occur outside the nuclear medium. The calculation of R_M^h is performed in pQCD; in addition to the leading order terms, the dominant twist-four term is also included. The twist-four term represents multiple scattering in the nuclear medium, and the contribution due to this term is a free parameter that can be fixed by comparison to data. This model was able to describe the HERMES krypton data by fitting the HERMES nitrogen data. The modification of the fragmentation functions represented by $R_M^h(z, \nu)$ emerges naturally from this description. In this approach, a novel quadratic dependence of the energy loss on path length is predicted, originating in the non-Abelian analog of the LPM effect in QED [13]. However, the assumption that hadronization occurs outside the nucleus will break down at low energies or for more massive hadrons.

Another recent model invokes deconfinement of nucleons in the nuclear medium as a mechanism for the modification of fragmentation functions in the nuclear medium [14]. The basic method follows the rescaling models developed in the 1980's. This approach combines partial deconfinement with absorption of the formed hadron in the nuclear medium. The nucleonic deconfinement effectively extends the range in Q^2 for which gluon radiation takes place, modifying the frag-

mentation functions accordingly. The model successfully describes the EMC data and the HERMES data for pions and K^+ in nitrogen and krypton, although the prediction for K^- systematically deviates from the data.

A fourth recent model adapts and improves stationary string model (SSM) techniques developed in the 1980's and 1990's. This model, applied to valence quarks, successfully fits the HERMES pion data for nitrogen and krypton, and predictions are given for kaons and heavier nuclei [15]. As with the previous model, the prediction for K^+ and K^- attenuations are very similar, while the HERMES data show a systematic difference.

Finally, an approach that emphasizes accurate modeling of the final state interactions (FSI) is able to explain the HERMES data without invoking modification of fragmentation functions [16]. The struck quark propagates, evolves into a hadron, and its interaction with the nuclear medium is given by a classical coupled-channel hydrodynamic calculation that has been tested in other reactions. These calculations, although in preliminary form, seem to have enough flexibility to reproduce the HERMES nitrogen and krypton data for charged pions and kaons, and protons and anti-protons. There is good qualitative agreement throughout, and quantitative agreement for some kinematics.

3.2. Connections between models and observables

The models highlighted above are generally able to describe the published data, in spite of the fact that they rely on quite different physical pictures. In order to make good progress in understanding hadron formation in nuclear DIS, it is necessary to discriminate among these models using more data that span a wider range of kinematics or that introduce new observables. Similarly, more complete calculations are needed. For instance, model predictions for the flavor and mass dependence of $R_M^h(z, \nu)$ can be tested by studying pions, kaons, and protons. In fact, a wide range of particles can be considered, as seen in Table 1. In this table, hadrons with $c\tau$ much greater than nuclear dimensions are listed. To the extent that hadronization is the production mechanism, inter-comparison of $R_M^h(z, \nu)$ for these particles will shed light on such topics as whether classical calculations of FSI suffice, or whether a quantum mechanical description is required. Likewise, study of moments of transverse momentum may distinguish between models with different assumptions about the number of multiple scatters or the shape of the emitted gluon momentum distribution. Measurements of R_M^h at low z may be useful, particularly at low energies, to distinguish between pion flux entering other reaction channels, as in FSI, from a change in the intrinsic fragmentation function, i.e., due to gluon emission. A clean evaluation of the Q^2 dependence of R_M^h will help distinguish between different reaction mechanisms. Studies of the angular correlations between two high-energy pions may also clarify whether the reaction mechanism is dominated by FSI in the nuclear medium or by the fragmentation process. Spin observables, such as single-spin asymmetries, may offer indications of whether partonic multiple scattering is an important component of the process.

TABLE 1. Final-state hadrons potentially accessible for formation length and transverse momentum broadening studies in CLAS. The rate estimates were obtained from the LEPTO event generator for an 11 GeV incident electron beam. (The criteria for selection of these particles was that $c\tau$ should be significantly larger than nuclear dimensions, and their decay channels should be measurable by CLAS⁺⁺.)

Hadron	$c\tau$	Mass (GeV)	Flavor content	Detection channel	Production rate per 1k DIS events
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	$\gamma\gamma$	1100
π^+	7.8 m	0.14	$u\bar{d}$	direct	1000
π^-	7.8 m	0.14	$d\bar{u}$	direct	1000
η	0.17 nm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	$\gamma\gamma$	120
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\pi^0$	170
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\eta$	27
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	K^+K^-	0.8
K^+	3.7 m	0.49	$u\bar{s}$	direct	75
K^-	3.7 m	0.49	$\bar{u}s$	direct	25
K^0	27 mm	0.50	$d\bar{s}$	$\pi^+\pi^-$	42
p	stable	0.94	ud	direct	1100
\bar{p}	stable	0.94	$\bar{u}\bar{d}$	direct	3
Λ	79 mm	1.1	uds	$p\pi^-$	72
$\Lambda(1520)$	13 fm	1.5	uds	$p\pi^-$	-
Σ^+	24 mm	1.2	us	$p\pi^0$	6
Σ^0	22 pm	1.2	uds	$\Lambda\gamma$	11
Ξ^0	87 mm	1.3	us	$\Lambda\pi^0$	0.6
Ξ^-	49 mm	1.3	ds	$\Lambda\pi^-$	0.9

Finally, the twist-4 pQCD model makes the assumption that hadronization takes place outside the nucleus altogether. The point at which this assumption is no longer valid is an important unknown that can be addressed by the CLAS low-energy data.

While these are rich and exciting prospects for learning much new physics, there are a few experimental and theoretical complications that require further study and clarification. For instance, hadron formation lengths can be derived from the data, however, the definition of the formation length depends on which model is considered. As an example, hadron formation is conceived as a multi-step process with multiple time constants in some models, but a single-step process in others. Reference frame considerations also enter the interpretation of the data; a lower limit on x is required to preserve the simple picture that a single quark propagates with initial energy ν [17]. Resonances in the residual system may need to be suppressed, which reduces the kinematic coverage available. There may be

an issue of isolating current fragmentation from target fragmentation, although the nuclear medium may perhaps suppress the latter. Finally, the degree of validity of QCD factorization needs to be evaluated. The last few issues are common to all semi-inclusive deep inelastic scattering, and as such are being investigated by several physics communities; further progress is therefore to be expected.

4. *Future prospects*

Over the next few years, it is expected that new datasets will become available which will provide further stringent tests of these models. Some HERMES data were taken with a 12 GeV beam on both nitrogen and krypton targets; 27 GeV data on helium and neon are also under analysis. A new program at Jefferson Lab will provide even lower energy data at high luminosity on targets ranging from carbon to lead. These 5 GeV data, from the CLAS EG2 running period, will have sufficient statistics to map out the full multivariate character of R_M^h for several hadron species, and to directly measure transverse momentum broadening.

Other future prospects include the possibility of additional targets in HERMES such as xenon, to complete the study of nuclear mass dependence at high energy transfer, and a large program which would be possible at Jefferson Lab following the energy upgrade. The ultimate moderate-energy program will be feasible with CLAS⁺⁺, due to the planned upgrade in luminosity (to $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$) and improved particle identification capabilities. These improvements will permit mapping out multivariate R_M^h for all the hadrons in Table 1 as well as p_T broadening for many of these, spanning a kinematic range of ν from 2 – 9 GeV and $2 - 9 \text{ GeV}^2$ in Q^2 .

5. *Conclusions*

The study of hadronization from semi-inclusive nuclear DIS is a new topic that is drawing increasing interest from several different physics communities. The recent wave of interest stimulated by the HERMES measurements has resulted in a number of theoretical efforts to describe the data. These efforts, based on a variety of physical pictures, demonstrate the exciting possibility of gaining new insight into hadronization as well as other aspects of quark propagation through nuclei such as quark energy loss. However, more data is needed to definitively discriminate among these model approaches. In addition, much more theoretical effort is needed to address all of the recent data, to reduce the number of assumptions in the models, and to make greater contact with the fundamental theory, QCD.

References

- [1] L. S. Osborne et al., Phys. Rev. Lett. **40** (1978) 1624.
- [2] EMC Coll., J. Ashman et al., Z. Phys. C **52** (1991) 1.

- [3] E665 Coll., M. R. Adams et al., Phys. Rev. D **50** (1994) 1836.
- [4] HERMES Coll., A. Airapetian et al., Eur. Phys. J. C **20** (2001) 479.
- [5] HERMES Coll., A. Airapetian et al., hep-ex/0307023 (2003).
- [6] HERMES Coll., K. Ackerstaff et al., Nucl. Instr. and Meth. A **417** (1998) 230.
- [7] B. A. Mecking et al., Nucl. Instr. Meth. A **503** (2003) 513.
- [8] X.-N. Wang, nucl-th/0307036 (2003).
- [9] STAR Coll., J. Adams et al., nucl-ex/0309012 (2003).
- [10] X. Guo and J. Qiu, Phys. Rev. D **61** (2000) 096003.
- [11] A. Bialas, T. Chmaj, Phys. Lett. B **133** (1983) 241.
- [12] B. Z. Kopeliovich, J. Nemchik and E. Predazzi, nucl-th/9607036 (1996).
- [13] SLAC E146 Coll., P. L. Anthony et al., Phys. Rev. D **56** (1997) 1373.
- [14] A. Accardi, V. Muccifora, H. J. Pirner, Nucl. Phys. A **720** (2003) 131.
- [15] N. Z. Akopov, G. M. Elbakian and L. A. Grigoryan, hep-ph/0205123, (2002).
- [16] T. Falter and U. Mosel, nucl-th/0308073 (2003).
- [17] V. D. Duca, S. J. Brodsky and P. Hoyer, Phys. Rev. D **46** (1992) 931.
- [18] P. L. McGaughey, J. M. Moss and J. C. Peng, Ann. Rev. Nucl. Part. Sci. **49** (1999) 217.

PROSTORNO-VREMENSKE ZNAČAJKE HADRONIZACIJE U DUBOKO NEELASTIČNOM RASPRŠENJU

Proučavanje hadronizacije, procesa kojim kvarkovi tvore hadrone, proučava se fenomenološki desetljećima. Međutim, prostorno-vremenske značajke tog u osnovi neperturbativnog procesa slabo su eksperimentalno istražene. Novi podaci u JLabu zajedno s podacima HERMES pružiti će važna nova saznanja o pojavama nastajanja hadrona u duboko neelastičnom raspršenju: gubitak energije kvarkova u jezgrama, tvorba gluona i obnavljanje polja boje.